INTERPRETATION OF SOLAR WIND COMPOSITION MEASUREMENTS FROM ULYSSES

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Final Report

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Final Report on the grant NAG5-4993 "Interpretation of Solar Wind Composition Measurements from ULYSSES"

1.1 SCOPE OF THE INVESTIGATION

Ion charge states measured in situ in interplanetary space carry information on the properties of the solar wind plasma in the inner corona. This information is, however, not easy to extract from the in situ observations. The goal of the proposal was to determine solar wind models and coronal observations that are necessary tools for the interpretation of charge state observations. It has been shown that the interpretation of the in situ ion fractions are heavily dependent on the assumptions about conditions in the inner corona.

1.2 PROGRESS MADE DURING PERIOD 10/1/97 - 9/30/98

There are three fields important to the interpretation of minor ion charge state measurements that we have concentrated on during this time interval. These are 1. Modeling of the charge state ratios of a number of ions commonly measured in situ, 2. Modeling of minor ion outflow properties, and 3. Measurements of the properties of minor ions and the background solar wind in the inner corona.

1. The interpretation of charge state observations in interplanetary space is only possible in the context of models since the ion ratios are extremely sensitive functions of the electron density, electron temperature and minor ion outflow speeds. In past studies it has always been assumed that the minor ion outflow speeds in the inner corona are of the order of a few km s^{-1} or even less. Following the results derived from recent UVCS coronal measurements, we have investigated the effect of high minor ion outflow speeds on the interpretation of in situ charge state measurements. Assuming Maxwellian velocity distribution we have shown that in the presence of high minor ion outflow speeds, like the ones derived from the UVCS observations for O^{+5}, electron temperatures in the inner corona have to be significantly higher than previously assumed. As a matter of fact, most likely higher than electron temperatures derived from line ratios observed in the inner corona with the SUMER instrument. If both, the electron temperatures are low in the inner corona, and the ion flow speeds are high, then the velocity distributions of the electrons have to deviate significantly from Maxwellian distribution functions in order to produce the charge states of the ions commonly observed in situ in the high speed solar wind (Esser et al. 1997). Figure 1b shows an example of how the formation temperature of the ions changes as a function of flow speed. This example was calculated to support the interpretation of Fe line intensity measurements carried out in the inner corona at the positions shown in Figure 1a.

2. Using a three fluid model of the solar wind we have continued to investigated the flow properties of heavy ions in the solar wind. It was found that by choosing appropriated heating functions for all the particles (electrons, protons and minor ions) solutions where the minor ions flow an Alfvén speed faster than the protons in interplanetary space can easily be achieved. In these type of solutions the minor ions have a tendency to be faster than the protons already very

close to the sun, in agreement with the recent UVCS observations. The distance where the protons are overtaken by the ions is typically at 2 R_S, a distance that could still be below the freezing in distance for the different charge states and therefore affect the formation of these charge states (see above) (e.g. Li et al. 1997).

3. Ion charge state formation in the inner corona depends on the electron density, in addition to the dependence on the electron temperature and ion flow speed. As a matter of fact, the density dependence is quite crucial in the charge state formation. We have therefore investigated limits on the electron densities in the very inner corona, below 2 R_S above the limb, which is the region important for the charge state formation. This is also the region where the electron densities which are commonly derived from polarization brightness measurements, are least accurate due to scattering from the solar disk. This is the reason why the spread of coronal hole densities derived from observations below 1.5 R_S is much larger than the spread in the observed values above that distance (see Figure 2a). Daily observations inside a coronal hole are shown in Figure 2b. These observations also show a large density variations in the inner corona, which are most likely caused by line-of-sight effects. We conducted a parameter study of electron densities in the lower solar atmosphere using a wide range of different atmospheric models. These models are constraint by spectral line observations and give as a function of height electron temperatures and densities. Comparing these electron densities with the observed coronal densities we noticed that regardless of the atmospheric models used, the electron densities derived from the atmospheric models will result in electron densities in the corona about one oreder of magnitude lower than observed electron densities in the corona. Studying line of sight effects in the corona over long periods of time, we concluded that the coronal electron densities are significantly biased by line of sight contribution from closed loop structures. These structures contribute mainly below 1.5 R_S, precisely in the region which is important for the formation of the charge states. Recent line ratio diagnostics from SUMER and CDS which make use of cooler lines, more relevant for coronal hole plasmas give electron densities almost one order of magnitude lower than the ones previously derived, or derived from higher temperature lines. We are presently studying by how much these lower densities would effect the charge state formation (Esser and Sasselov 1999).

In addition we have continued to study minor ions in the inner corona using UVCS. UVCS is presently the only instrument that can give minor ion information in the region above 2 R_S, a region which for many ions is still important for their formation. We have carried out a long series of observations to place limits on the properties of Mg X which is one of the ions that is observed with the SWICS instrument on ULYSSES. These observations reveal that these ions are significantly hotter than the protons, even though slightly cooler than she O VI ions. Since the pressure force plays an important role in the acceleration of the ions, the fact that the Mg ions are like the O ions significantly hotter than the protons indicates that these ions also flow fast in the inner corona. We are presently using that information to study the formation of the Mg X in a more consistent manner (Esser et al. 1999; Kohl and Esser et al. 1999). Figures 3 summarize the results of these studies.

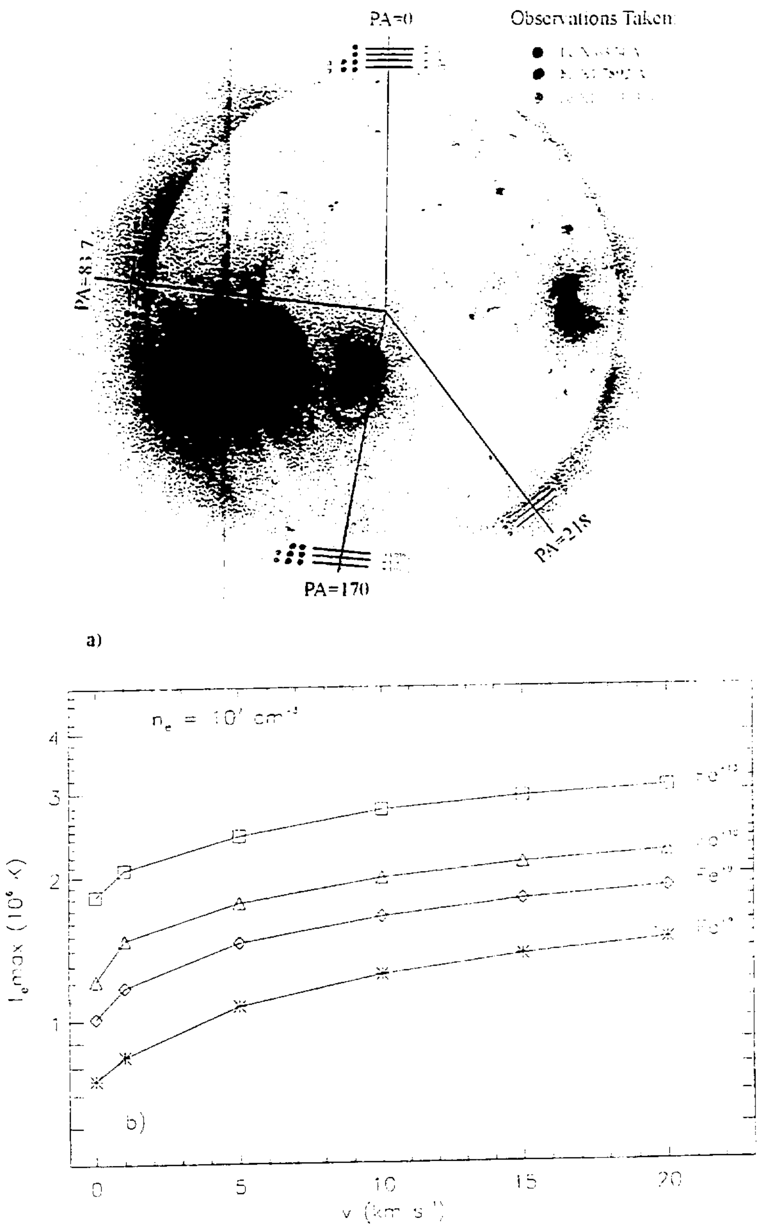

Figure 1 : (a) Soft X-ray YOHKOH image together with the position of coordinated spectral line measurements carried out at the National Solar Observatory at Sacramento Peak. (b) Increase of the peak temperature of formation with flow speed.

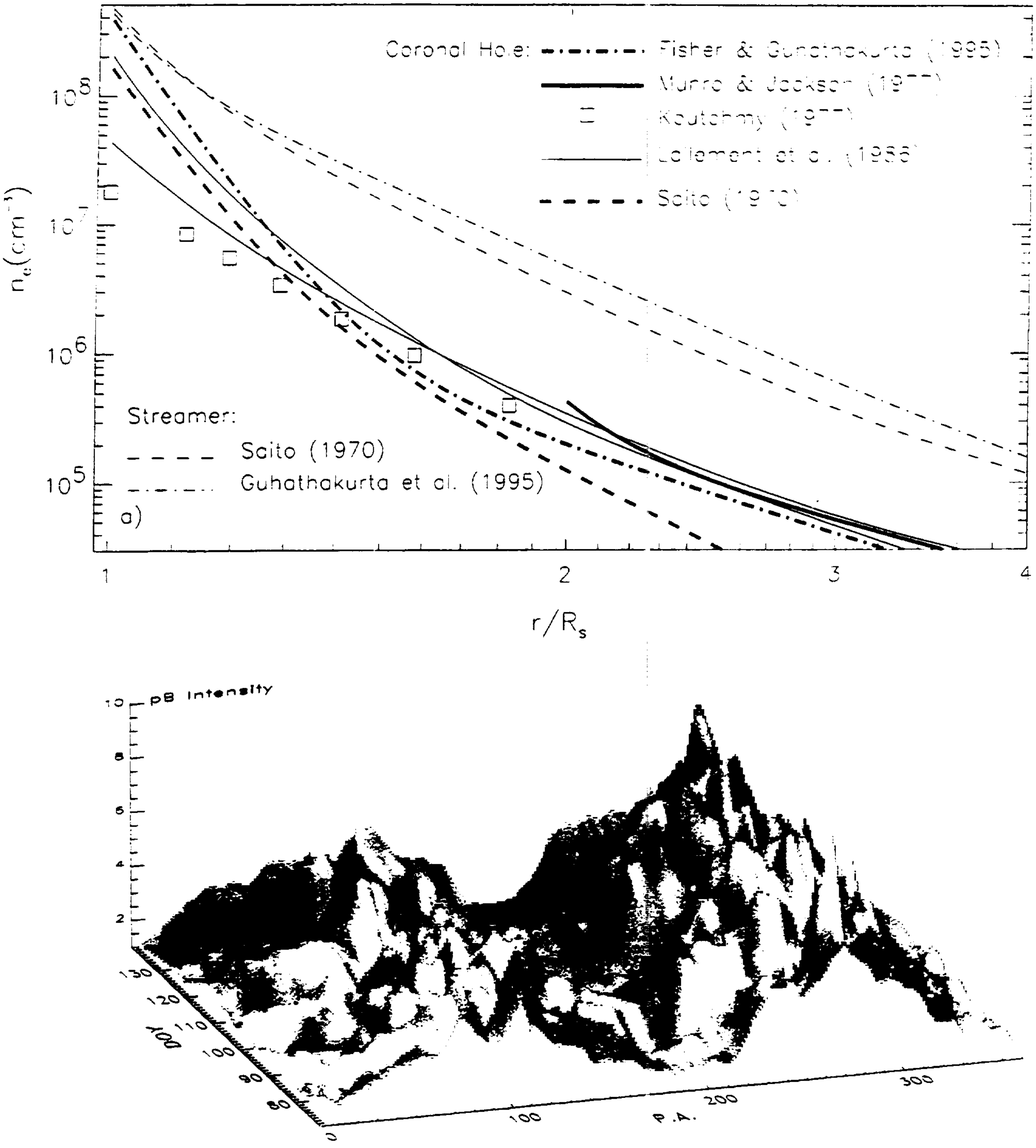

Figure 2 : (a) Coronal electron densities derived from a number of different space and ground based observations. Note that the discrepancy between the coronal hole densities in the region 2 to 3 R_S is relatively small (a factor of 2 to 4), whereas the discrepancy in the region below 1.5 R_S increases to a factor of 20, with the highest coronal hole densities approaching streamer densities. (b) Daily Mauna Loa white light intensity measurements carried out at 1.16 R_S as a function of position angle, from March 12 to May 19 1993 which is the time period surrounding the SPARTAN pB measurements of April 12 in (a). Note the large daily density variations in both southern and northern coronal holes.

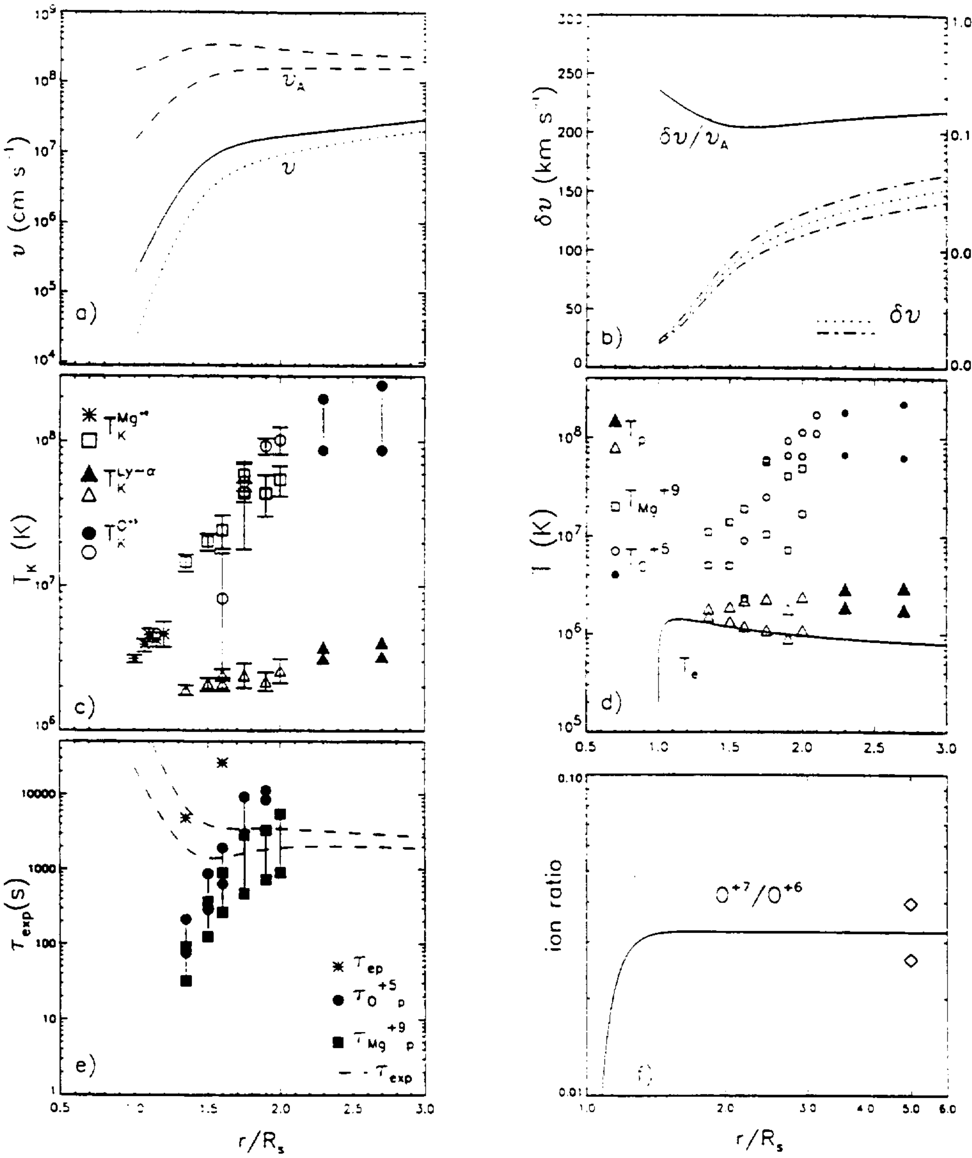

Figure 3: (a) Flow speeds derived from the assumption of mass flux conservation and the Fisher and Guhathakurta (1995) coronal electron densities (Figure 1a) and a proton flux of 1.6 to 2.2 $\times 10^8 cm^{-2} s^{-1}$ (e.g. Phillips et al. 1995). The flow speeds and densities, together with the assumption of magnetic flux conservation are used to place limits on the Alfvén speed. (b) Limits on the Alfvén wave amplitude (dashed lines) derived from the kinetic ion temperatures in (c) and WKB approximation. WKB approximation is also used to calculate corresponding SUMER values (Tu and Marsch 1998) (dotted line). It is usually assumed that Alfvén waves do not damp if $\delta v / v_A << 1$, which is clearly the case for the distances shown in the figure. (c) UVCS line widths for three different spectral lines (see text), supplemented for Mg X with observations from Hassler et al. (1990). (d) Thermal contribution to the line broadening calculated from (c) and (b). (e) Equipartition times for energy exchange between protons and heavy ions, and proton and electrons, calculated from the densities and temperatures above. Limits on the solar wind expansion times are also shown (dashed lines). (f) Oxygen ion fraction calculated for the same electron densities used in (a), and ion outflow speeds close to the ones in Figure 2d, compared to the observed ULYSSES values (see Esser et al. 1998a for details).

2. Publications in Journals and Proceedings Fully or Partially Funded by the Grant

1. X. Li, R. Esser, S. R. Habbal, and Y.-Q. Hu, Influence of heavy ions on the solar wind, submitted to *J. Geophys. Res.*, **102**, 17419, 1997..

2. R. Esser, R. J. Edgar and N. S. Brickhouse, High minor ion outflow speeds in the inner corona and observed ion charge states in interplanetary space, *Astrophys. J.*, **498**, 448, 1998.

3. R. Esser, S. Fineschi, D. Dobrzycka, S. R. Habbal, R. J. Edgar, J. C. Raymond, and J. L. Kohl, Plasma properties in coronal holes derived from measurements of minor ion spectral lines and polarized white light intensity, *Astrophys. J. Let.*, January, 1999.

4. J. Kohl, R. Esser, S. Fineschi, R. Frazin, L. Gardner, A. Panasuk, R. Suleiman, S. Cranmer and G. Noci, EUV spectral line profiles in polar coronal holes from 1.3 to 3. R_S, *Astrophys. J. Let.*, January, 1999.

5. P. Young and R. Esser, Temperature and density in coronal holes - results from CDS/SOHO, to be published in SW9 proceedings, 1999.

6. P. Young and R. Esser, Comparing quiet sun and coronal hole regions with CDS/SOHO, to be published in SOHO7 proceedings, 1999.

7. C. Halas, S. Habbal, R. Esser, M. Penn, and D. McKenzie, Inferences of plasma parameters in coronal holes and streamers, to be published in proceedings of the SW9 conference, 1999.

8. E. Kaghashvili and R. Esser, Density fluctuations observed in the inner corona: Possible mechanism, to be published in Proceedings of the SW9 conference, 1999.

9. R. Esser and D. Sasselov, Discrepancy between atmospheric and coronal densities, *J. Astrophys. Res. Let.*, submitted, 1998.